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Kim K. de Groh  
*Lewis Research Center*  
*Cleveland, Ohio*

David M. Roig and Christopher A. Burke  
*Cleveland State University*  
*Cleveland, Ohio*

and

Dilipkumar R. Shah  
*AlliedSignal Aerospace Company*  
*Torrance, California*

Prepared for the  
1994 ASME International Solar Energy Conference  
sponsored by the  
American Society of Mechanical Engineers  
San Francisco, California, March 27-30, 1994



(NASA-TM-106549) PERFORMANCE AND  
DURABILITY OF HIGH EMITTANCE HEAT  
RECEIVER SURFACES FOR SOLAR DYNAMIC  
POWER SYSTEMS (NASA. Lewis  
Research Center) 16 p

N94-28834

Unclass

G3/20 0003006

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# PERFORMANCE AND DURABILITY OF HIGH EMITTANCE HEAT RECEIVER SURFACES FOR SOLAR DYNAMIC POWER SYSTEMS

Kim K. de Groh  
Electro-Physics Branch  
NASA Lewis Research Center  
Cleveland, Ohio

David M. Roig, Physics Department  
Christopher A. Burke, Mechanical Engineering Department  
Cleveland State University  
Cleveland, Ohio

Dilipkumar R. Shah  
Aerospace Systems & Equipment  
AlliedSignal Aerospace Company  
Torrance, California

## ABSTRACT

Haynes 188, a cobalt-based superalloy, will be used to make thermal energy storage (TES) containment canisters for a 2 kW solar dynamic ground test demonstrator (SD GTD). Haynes 188 containment canisters with a high thermal emittance ( $\epsilon$ ) are desired for radiating heat away from local hot spots, improving the heating distribution, which will in turn improve canister service life. In addition to needing a high emittance, the surface needs to be durable in an elevated temperature, high vacuum ( $\approx 830^\circ\text{C}$ ,  $<10^{-7}$  torr) environment for an extended time period.

Thirty-five Haynes 188 samples were exposed to 14 different types of surface modification techniques for emittance and vacuum heat treatment (VHT) durability enhancement evaluation. Optical properties were obtained for the modified surfaces. Emittance enhanced samples were exposed to VHT for up to 2692 hours at  $827^\circ\text{C}$  and  $\leq 10^{-6}$  torr with integral thermal cycling. Optical properties were taken intermittently during exposure, and after final VHT exposure.

The various surface modification treatments increased the emittance of pristine Haynes 188 from 0.11 up to 0.86. Seven different surface modification techniques were found to provide surfaces which met the SD GTD receiver VHT durability requirement ( $\epsilon \geq 0.70$  after 1000 hrs). Of the 7 surface treatments, 2 were found to display excellent VHT durability: an alumina based (AB) coating ( $\epsilon = 0.85$  after 2695 VHT hrs) and a zirconia based coating ( $\epsilon = 0.86$  after 2024.3 VHT hrs). The alumina based coating was chosen for the  $\epsilon$  enhancement surface modification technique for the SD GTD receiver. Details of the performance and vacuum heat treatment durability of this coating and other Haynes 188 emittance surface modification techniques are discussed. Technology from this program will lead to successful demonstration of solar dynamic power for space applications, and has potential for application in other systems requiring high emittance surfaces.

## INTRODUCTION

Solar dynamic power systems have been investigated for electrical power generation on Space Station Freedom (SSF) and other space systems. In a solar dynamic power system, a solar concentrator reflects focused solar energy into a receiver to operate a heat engine. Solar dynamic systems investigated by NASA for use on SSF would use a closed-Brayton cycle heat engine, generating 25 kW of power.<sup>1</sup> A 2 kW prototype solar dynamic ground test demonstrator is currently being built to demonstrate solar dynamic technology.<sup>2</sup> The SD GTD, managed by NASA Lewis Research Center (LeRC), will demonstrate production of solar dynamic power for 1000 hours in LeRC's large thermal/vacuum space environmental facility (see Figure 1).<sup>2</sup> Completion of fabrication of the 2 kW system and its initial testing is scheduled for Spring of 1995.<sup>2</sup>

The heat receiver for the SD GTD system is based on the design investigated for the SSF 25 kW system.<sup>3,4</sup> Inside the receiver (see Figure 2), solar energy is transferred to a Xe-He gaseous working fluid in a closed-Brayton heat engine through thermal energy storage containment canisters.<sup>4</sup> The canisters contain TES material, also known as phase change material (PCM), which stores the heat of fusion of a mixture of salts (LiF-CaF<sub>2</sub> eutectic salt) to provide heat for power generation during the substantial eclipse portion of the orbit.

The receiver TES containment canisters and working fluid tubes are being made of Haynes 188, a cobalt-based superalloy. Haynes 188 containment canisters with high thermal emittance surfaces are desired for radiating heat away from local hot spots. This will greatly improve the heating distribution inside the receiver and improve canister service life. Because the heat receiver will operate at elevated temperatures ( $\approx 827^\circ\text{C}$ ) in a vacuum environment ( $\leq 10^{-6}$  torr) in both space and in the simulated space chamber, the high emittance surface needs to be durable in these hostile environments and resist optical property

degradation. Surface chemistry and morphological changes which may occur due to sublimation, diffusion and thermal relaxation at elevated temperature under vacuum could adversely effect optical properties. Research programs were initiated first in 1989 under the SSF SD program with the Electro-Physics Branch at NASA LeRC, and recently under the SD GTD program jointly with the Electro-Physics Branch at NASA LeRC and AlliedSignal Aerospace Company to investigate development of durable high emittance Haynes 188 surfaces for heat receiver applications.

The SSF emittance program investigated various surface modification techniques to improve the Haynes 188 surface emittance. Under this program, four samples were exposed to extended elevated temperature (827°C) vacuum heat treatment (VHT).<sup>5</sup> Samples were also evaluated for elevated temperature atomic oxygen durability.<sup>5</sup> It was found that SiC grit blasting the Haynes surface followed by air oxidation produced a high emittance surface. The oxidized surfaces were found to provide initial protection against sublimation-related surface changes, but the oxide was found to be unstable over extended elevated temperature vacuum exposures (5215.5 hrs) and the protection was not permanent.<sup>5</sup> The SD GTD emittance program was initiated to continue investigations of Haynes 188 surface modification, with a stronger emphasis on developing a high emittance surface which would be environmentally durable, with little or no change in emittance after 1000 hours of VHT exposure.

Under the SD GTD emittance program, 35 Haynes 188 samples were exposed to 14 different types of surface modification techniques for emittance and vacuum heat treat durability enhancement. The emittance enhancement techniques included grit blasting followed by air oxidation, arc texturing, mechanically indenting followed by air oxidation, laser treatment, and the application of alumina and zirconia based coatings. Additionally, SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> coatings were applied for durability enhancement. Emittance, absorptance and mass measurements were obtained for the modified surfaces. Emittance-enhanced test samples were exposed to vacuum heat treatment (VHT) for up to 2692 hours at 827°C and  $\leq 10^{-6}$  torr. Samples were also thermal cycled during VHT between 827°C and room temperature at  $\approx 100$  hour intervals. Optical property measurements were taken before, during and after VHT exposure. Details of the emittance performance of samples which underwent various surface modification techniques are explored along with their VHT durability, and the recommended surface modification for use on the SD GTD receiver are discussed in this paper.

## EXPERIMENTAL PROCEDURES

### Material

Surface modifications and optical property characterizations were conducted on 2.53 cm diameter, 0.16 cm thick Haynes 188 sample coupons. Haynes 188, contains  $\approx 38.0\%$  (by weight) Co, 23.03% Ni, 21.69% Cr, 14.02% W, 1.95% Fe,  $<1\%$  Mn, Si, P, C, La, and trace amounts of B and S.

## Surface Modification Techniques for Emittance Enhancement

### Surface Texturing

**Grit Blasting and Air Oxidation.** Grit blasting with 60  $\mu\text{m}$  SiC grit followed by air oxidation was re-evaluated based on the good emittance values obtained under the SSF emittance program.<sup>5</sup> The SSF emittance program indicated that the oxide film formed during air oxidation became embrittled and non-adherent after long term VHT (5215.5 hrs at 827°C).<sup>5</sup> Therefore, it was believed that a thinner oxide film would maintain better adherence, and hence better  $\epsilon$ , with anticipated thermal cycling. Several temperature and time variations were examined in an attempt to evaluate the effect of variation in oxide thickness on emissivity under long term VHT exposure. The various temperature/time combinations evaluated were: (a) 982°C for 2 hrs, 4 hrs and 16 hrs, and (b) 871°C for 3 hrs, 6 hrs and 24 hrs.

**Physical Texturing.** Other types of physical texturing techniques were explored to increase the surface roughness and therefore the thermal emittance of the Haynes 188 surface. One sample was mechanically indented by a mechanical vibration pen. This sample was then subjected to air oxidation (871°C/24 hrs) for further emittance enhancement. A second sample was mechanically indented with application of graphite in an attempt to simulate carbon inclusion into the surface like arc texturing described below. A third sample was prepared using computer controlled laser etching over the surface of the Haynes coupon, until a uniform texture appearance was obtained.

**Arc Texturing.** A combination of physical roughening and chemical altering was explored by arc texturing the Haynes surface. Carbon-rod arc texturing has been demonstrated to produce a high emittance surface for space radiator applications.<sup>6</sup> Arc texturing was accomplished by producing an electric arc discharge between an electrode (typically C) and the Haynes substrate material. A uniform texture was produced by slowly moving the arc over the sample surface in either air or an inert atmosphere until a uniform dark appearance was achieved. Metal from the Haynes 188 surface and the arc electrode material (C or SiC) vaporized during arcing and condensed onto the Haynes surface to produce a microscopically rough surface.<sup>6</sup> Both C and SiC electrodes were used, with the C arc texturing performed in an argon atmosphere, and SiC arc texturing performed in air. Although arc texturing using a carbon electrode is most common, SiC was investigated in attempt to provide the chemistry which would allow development of an adherent SiC protective layer that could convert to SiO<sub>2</sub> during VHT.

### Coatings for Emittance Enhancement

**Zirconia Based (ZB) Coatings.** Two coatings used for thermal barrier applications were evaluated for emittance enhancement with potential integral VHT durability. Both were

zirconia based coatings (composition #1 and #2) and are designated ZB-1 and ZB-2. Details of these coatings are provided in the NASA TM bearing the same title as this paper, which can be obtained through the primary author. Both zirconia based coatings were originally deposited with 0.254 mm thicknesses. However, thermal barrier concerns for this application resulted in preparation and evaluation of samples with thinner ZB-1 coatings. The effect of thickness on both the optical performance and VHT durability was evaluated. These additional ZB-1 coatings were 0.025 mm, 0.056 mm, 0.071 mm, and 0.104 mm thick.

**Alumina Based (AB) Coating.** An alumina based coating was also evaluated for potential combined emittance enhancement with integral VHT durability. This coating is designated AB, to avoid confusion with the  $\text{Al}_2\text{O}_3$  protective coating. Two thicknesses of the AB coating were evaluated (0.025 mm and 0.051 mm). Details of the alumina based coating are provided in the above mention NASA TM.

#### Protective Coatings for Durability Enhancement ( $\text{SiO}_2$ and $\text{Al}_2\text{O}_3$ )

The SSF emittance study provided evidence of sublimation of Haynes 188 high vapor pressure materials (Cr, Co, & Ni).<sup>5</sup> Therefore, it was decided to evaluate the application of protective coatings on top of grit blast and air oxidized samples and also on the C arc textured samples. The protective coatings were expected to protect the underlying high emittance surface by forming a diffusion barrier and/or acting as a sacrificial sublimation layer and reduce the degradation of optical properties of the high emittance surface. Two metal oxide thin film protective layers,  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$ , were evaluated. Because the protective coatings were applied onto microscopically rough surfaces, both physical vapor deposition (PVD) which produces line-of-site deposition, and chemical vapor deposition (CVD) which produces conformal deposition, were evaluated for protective ability.

The PVD technique used was electron beam evaporation. To help promote uniform coverage during electron beam evaporation, the samples were coated at  $45^\circ$  angles, then rotated  $90^\circ$  and coated again. The precursor material for CVD deposition of  $\text{SiO}_2$  was tetraethoxysilane with an argon carrier gas. The substrate temperature was maintained at  $300^\circ\text{C}$ , and the pressure was kept at 0.8-0.9 torr. The precursor for CVD deposition of  $\text{Al}_2\text{O}_3$  was aluminum triisopropoxide. The substrate temperature was kept at  $325^\circ\text{C}$ , and the pressure was kept at 0.8 torr. Both CVD and PVD protective coatings were between 1000 and 1300 Å thick.

#### Characterization

**Optical Properties.** Thermal emittance at  $827^\circ\text{C}$  ( $\epsilon_{827^\circ\text{C}}$ ) was originally obtained using data from both a Hohlraum Reflectometer and a Perkin-Elmer  $\lambda$ -9 Spectrophotometer. The

Hohlraum Reflectometer was used to obtain spectral emittance over the wavelength range from 1700 to 14,700 nm. The  $\lambda$ -9 was used to obtain spectral emittance over the wavelength range 400 to 2500 nm. The spectral data from both instruments were weighted in the overlap area, and the integrated thermal emittance at  $827^\circ\text{C}$  was obtained by convoluting this spectrum into the blackbody distribution function at  $827^\circ\text{C}$ .<sup>7</sup> Thermal emittance uncertainty is  $\pm 10\%$ . Although this was the desired method for obtaining thermal emittance, unavailability of the Hohlraum Reflectometer during the later part of testing resulted in obtaining data on the spectral emittance at  $827^\circ\text{C}$ .

The spectral emittance at  $827^\circ\text{C}$  ( $\epsilon_{827^\circ\text{C}\lambda}$ ) was obtained using the  $\lambda$ -9 Spectrophotometer. Hemispherical reflectance was measured at 2634 nm, the wavelength of the peak emissive power of the  $827^\circ\text{C}$  blackbody curve. The spectral absorptance ( $\alpha_\lambda$ ) at 2634 nm was obtained by subtracting the spectral reflectance from 1. The spectral emittance for  $827^\circ\text{C}$  was then obtained based on Kirchhoff's Law ( $\epsilon_\lambda = \alpha_\lambda$ ).<sup>8</sup> Spectral reflectance uncertainty is  $\pm 2\%$ . Comparisons of spectral emittance at  $827^\circ\text{C}$  and integrated thermal emittance at  $827^\circ\text{C}$  for several samples showed good correlation (typically within  $\pm 3\%$ ). Because the thermal emittance durability was a critical issue, it was decided this technique was appropriate for determining emittance changes with VHT exposure.

Solar absorptance was obtained on a Perkin-Elmer  $\lambda$ -9 Spectrophotometer operated with a 60 mm integrating sphere. Total spectral reflectance was obtained over the wavelength range 250-2500 nm. Integrated solar hemispherical reflectance was obtained by convoluting the spectrum into the air mass zero (AM0) solar spectrum over the same range. Solar absorptance was then calculated by subtracting the solar hemispherical reflectance from 1. A few of the acquired spectra were convoluted into the SD GTD solar simulator spectrum (for a xenon arc-lamp) to compare AM0 solar absorptance with solar simulator absorptance.

**Oxide Thickness.** The oxide thickness of two grit blast and air oxidized samples ( $982^\circ\text{C}$  for 4 and 16 hours) was determined. These samples were cross-sectioned, mounted, and metallographically prepared for optical microscopy examination. The oxide thickness resulting from the two air oxidation treatments was then determined by measuring oxide thickness from micrograph images obtained at 1000 X.

#### Vacuum Heat Treatment

Surface treated samples were heated to  $820^\circ\text{C}$  in a vacuum environment of  $\leq 10^{-6}$  torr between 1159.3 and 2692 hours. Test samples did not receive identical exposure durations because various samples were fabricated and introduced into the vacuum furnace over a period of time. The SSF emittance program provided evidence of embrittlement of the heat treated high emittance surface.<sup>5</sup> It was anticipated that thermal cycling may accelerate optical property degradation through spalling of the embrittled surfaces. Therefore, thermal vacuum exposure was programmed to include 100 hour thermal cycles ( $820^\circ\text{C}$  to room

temperature) without breaking vacuum. Thermal cycling at 100 hour intervals simulated the anticipated cycling which could occur during SD GTD operation. Thermal cycling interruptions with corresponding vacuum breaks were experienced due to facility shut-downs, planned interruptions for sample characterization, or introduction of more samples into the thermal vacuum facility. Optical property and mass measurements were taken periodically during VHT exposure.

## RESULTS AND DISCUSSION

### Optical Properties ( $\epsilon$ and $\alpha_s$ ) prior to VHT

**Effect of Surface Modification on  $\epsilon$  and  $\alpha_s$ .** The thermal emittance at 827°C ( $\epsilon_{827^\circ\text{C}}$ ), spectral emittance at 827°C ( $\epsilon_{827^\circ\text{C}\cdot}$ ) and solar absorptance ( $\alpha_s$ ) for pristine Haynes 188 were 0.14, 0.08 and 0.370, respectively. The results of the various surface modifications on the as-treated optical properties of Haynes 188 are summarized in Table 1. A bar graph, shown in Figure 3, graphically shows the range and tailorability of the Haynes 188 emittance through surface modification. Table 1 does not include samples which were coated with  $\text{SiO}_2$  or  $\text{Al}_2\text{O}_3$  protective coatings. In this graph, and all following graphs,  $\epsilon$  is given as an average of  $\epsilon_{827^\circ\text{C}}$  and  $\epsilon_{827^\circ\text{C}\cdot}$  for pristine samples when both values are available, whereas  $\epsilon_{827^\circ\text{C}\cdot}$  is given for VHT values. It should be noted that for each surface treatment, the pristine values ( $\epsilon_{827^\circ\text{C}}$ ,  $\epsilon_{827^\circ\text{C}\cdot}$ , and  $\alpha_s$ ) were not necessarily obtained from the same sample.

Comparisons of AM0 solar absorptance (data integrated with respect to the solar spectrum at AM0), and solar simulator absorptance (data integrated with respect to the solar simulator spectrum), were made for the samples with AB coatings. The variation between the values were within experimental error; therefore, solar absorptance values originally obtained are listed instead of solar simulator values.

The desired thermal emittance for the SD GTD receiver canisters was 0.80. Four different surface modification techniques were found to increase the emittance of Haynes 188 from 0.14 to 0.80 or above. These surface modification treatments were: the application of an alumina based coating, carbon arc texturing, SiC arc texturing, and SiC grit blasting followed by air oxidation at 871°C, as shown in Table 1 and Figure 3. The  $\epsilon$  values for samples treated with laser etching and prepared with ZB-2 coatings were low (0.40 and 0.28, respectively) and are not discussed further.

### Effect of Air Oxidation Temperature and Time on $\epsilon$ and $\alpha_s$

**$\alpha_s$ .** Air oxidizing at 871°C gave better optical performance ( $\epsilon$  and  $\alpha_s$ ) than air oxidizing at 982°C. Grit blasting followed by air oxidation at 871°C for 3, 6, or 24 hours resulted in an  $\epsilon$  of  $0.79 \pm 0.02$  and  $\alpha_s$  of  $0.905 \pm 0.007$ . Grit blasting followed by air oxidation at 982°C for 2, 4, or 16 hours resulted in an  $\epsilon$  of  $0.72 \pm 0.01$  and  $\alpha_s$  of  $0.892 \pm 0.003$ . There also appeared to be a trend for slightly higher  $\epsilon$ , but not higher  $\alpha_s$ , for the samples with shorter oxidation times at either 871°C or 982°C.

Table 2 lists the individual air oxidized samples and their resulting optical properties.

The oxide thicknesses measured for the 2 samples oxidized at 982°C for 4 and 16 hours were  $2.8 \pm 0.4 \mu\text{m}$  and  $3.9 \pm 0.1 \mu\text{m}$ , respectively. Optical microscopy revealed two oxide layers, an inner layer believed to be  $\text{Cr}_2\text{O}_3$ , and an outer layer believed to be a spinodal composition. The inner layer was almost the same thickness for the two samples ( $1.3 \pm 0.1 \mu\text{m}$  for 4 hrs, and  $1.2 \pm 0.1 \mu\text{m}$  for 16 hrs), while the outer layer varied in thickness ( $1.5 \pm 0.4 \mu\text{m}$  for 4 hrs and  $2.7 \pm 0.1 \mu\text{m}$  for 16 hrs).

### Mechanical Texturing vs. Grit blasting Prior to

**Oxidation.** Silicon carbide grit blasting followed by air oxidation at 871°C for 24 hours resulted in significantly better optical performance than mechanically indenting, followed by air oxidation for the same time and temperature. As can be seen in Table 2, the  $\epsilon$  and  $\alpha_s$  for grit blasting prior to air oxidation was 0.77 and 0.912, respectively, and 0.68 and 0.890 for mechanically indenting prior to air oxidation.

### Effect of Coating Thickness (ZB-1 and AB) on $\epsilon$ and $\alpha_s$

Table 3 lists two AB coating thicknesses, and five ZB-1 coating thicknesses, and the corresponding optical properties for the as-deposited coatings. For both AB and ZB-1 coatings, the thickness did not have a notable effect on the optical properties. The thinner (0.025 mm) ZB-1 coating had slightly higher  $\epsilon$  and  $\alpha_s$  values of 0.75 and 0.879, respectively, than the thicker coatings (0.254 mm) with  $\epsilon$  and  $\alpha_s$  of 0.72 and 0.852, respectively. Composition variations from batch to batch may have contributed to these differences. Based on as-deposited performance, thinner AB and ZB-1 coatings would be more desirable due to lower thermal barrier effects. However, calculations from a 1-D infinite slab thermal analysis that evaluated the effect of coating thickness on a Haynes substrate has shown that either of these coatings could be applied at 0.254 mm thickness with a negligible effect on heat transfer to the TES salt and working fluid.

### C vs. SiC Arc texturing vs. Mechanical Indenting with Graphite Application

Both C and SiC electrode arc texturing resulted in very high  $\epsilon$  and  $\alpha_s$  values, see Table 4. As mentioned previously, C arc texturing resulted in an average  $\epsilon$  of 0.82 and an  $\alpha_s$  of 0.906. Silicone carbide arc texturing resulted in an  $\epsilon$  of 0.80 and an  $\alpha_s$  of 0.914. These values could vary from one sample to another because they were arc textured in a sweeping motion until they appeared to darken no further. Because this was done by hand, judgement of complete darkening introduced human error. This variation was apparent in the carbon arc textured sample values. The  $\epsilon_{827^\circ\text{C}}$  and  $\epsilon_{827^\circ\text{C}\cdot}$  values obtained from two different samples were quite different (0.77 and 0.86, respectively).

Mechanically indenting with application of graphite, in an attempt to simulate C incorporation into the surface such as arc texturing accomplishes, did not result in very good optical properties. The  $\epsilon$  and  $\alpha_s$  were only 0.42 and 0.516, respectively.

This technique was considered unsuccessful compared to arc texturing.

#### Effect of SiO<sub>2</sub> or Al<sub>2</sub>O<sub>3</sub> Protective Coatings on $\epsilon$ and $\alpha_s$

For the SiC grit blasted and air oxidized samples, the subsequent application of an SiO<sub>2</sub> or Al<sub>2</sub>O<sub>3</sub> protective coating resulted in a variation of effects on the optical properties. For shorter air oxidation times at both 871°C and 982°C (2-6 hrs) the application of a CVD SiO<sub>2</sub> coating resulted in a decrease in  $\epsilon$ , see Table 2. The amount of absolute decrease varied from 0.03 and 0.04 for 871°C (3 and 6 hrs, respectively), to 0.16 and 0.17 for 982°C (2 and 4 hrs, respectively). For the longer air oxidation time at 871°C (24 hrs), the  $\epsilon$  increased slightly from 0.77 to 0.80 and 0.79 for PVD and CVD SiO<sub>2</sub> coatings, respectively, and remained the same with a CVD Al<sub>2</sub>O<sub>3</sub> coating, while the  $\epsilon$  increased from 0.71 to 0.73 for 982°C at 16 hours with a PVD SiO<sub>2</sub> coating and decreased to 0.58 with a CVD SiO<sub>2</sub> coating.

In summary, the application of a PVD SiO<sub>2</sub> coating increased the  $\epsilon$  slightly, while the application of a CVD SiO<sub>2</sub> coating generally decreased the  $\epsilon$  from a slight amount to a large extent. There are two possible explanations for these effects. The first possibility is the variation of defects and impurities in the deposited oxide coating with the individual techniques. Small amounts of C and H from the precursor material are known to be incorporated into CVD SiO<sub>2</sub> coatings. Defects and impurities cause optical property changes such as color center formations.<sup>9</sup> The second possible explanation for the large variations in emittance may be due to variations in the oxide thickness. For example, there is significant fluctuation in the spectral emittance of silica on a silicon substrate as a function of oxide thickness.<sup>10</sup> Reference 10 shows the spectral emittance at  $\lambda = 694.3$  nm ( $T = 1300^\circ\text{C}$ ) fluctuating from  $\approx 0.58$  to  $\approx 0.85$  for every  $\approx 112$  nm additional thickness of silica. Each of these effects may be sufficient alone to cause the observed emittance variations, but it is more likely to be a synergistic effect of the two.

#### Optical Properties ( $\epsilon$ and $\alpha_s$ ) after VHT

##### Effect of Air Oxidation Temperature and Time on VHT

Durability. There was a significant effect of oxidation temperature and time, on the VHT durability of grit blast and air oxidized Haynes 188 samples. As can be seen in Figure 4, the sample likely to have the thickest oxide (982°C for 16 hrs) was found to be very durable, with no degradation in  $\epsilon$ , after VHT exposure for 2044.2 hours. The sample with the presumably thinnest oxide (871°C for 3 hrs) was found to degrade very rapidly with the worst VHT durability performance. These results indicated that in addition to providing a high emittance, air oxidizing formed an inherent protective coating with the protective ability depending on the oxide thickness. The formation of a protective coating is in agreement with the previous findings from the SSF emittance program<sup>5</sup> and alloy evaporation studies by Bourgette<sup>11</sup>. The 982°C/16 hour air

oxidized sample exposed in the current emittance program received 20 thermal cycles, and this sample along with all other air oxidized samples, indicated no signs of embrittlement or spalling after 2044.2 hours VHT exposure. These findings did not support the previously mentioned belief that a thinner oxide would maintain better adherence and hence better  $\epsilon$  with thermal cycling. The oxide embrittlement displayed in the SSF emittance program<sup>5</sup> may be attributed to the additional exposure time (total of 5215.5 hrs), or may have been affected by the Al, Ca and Mg contamination which occurred during VHT exposure.

##### Effect of SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> Protective Coatings on VHT Durability.

For samples which were grit blasted and then air oxidized at 871°C for 24 hours, the subsequent application of a PVD SiO<sub>2</sub> coating provided a slight improvement in the VHT durability compared to the sample with no additional protective coating (see Figure 5). But, for an unexplained reason, the application of either a CVD SiO<sub>2</sub> coating or a CVD Al<sub>2</sub>O<sub>3</sub> coating decreased the VHT durability. As can be seen in Figure 5, the CVD Al<sub>2</sub>O<sub>3</sub> coating performed slightly worse compared to the CVD SiO<sub>2</sub> coating. Because the vapor pressure of Al<sub>2</sub>O<sub>3</sub> is lower than SiO<sub>2</sub>, the opposite effect was expected. Although a CVD SiO<sub>2</sub> coating was found to degrade the VHT durability of the sample air oxidized at 871°C for 24 hours, neither a PVD nor a CVD SiO<sub>2</sub> coating significantly harmed or helped the VHT durability of the sample air oxidized at 982°C for 16 hours (see Figure 6). In this case, there was a slight advantage of the CVD coating over the PVD coating.

The application of additional protective coatings (SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>) to samples with thick air oxidized surfaces (982°C/16 hrs and 871°C/24 hrs) gave inconsistent results. Both small benefits and harmful effects were observed. For samples air oxidized with thin oxide surfaces, three out of four samples (871°C/3 hrs, 982°C/2 hrs and 982°C/4 hrs) showed significant increases in the VHT durability with the addition of a CVD SiO<sub>2</sub> protective layer (see Figure 7). In general, the application of SiO<sub>2</sub> protective coatings benefits air oxidized samples with thin oxide surfaces, but air oxidized surfaces with thick oxides form inherent protective coatings, and additional SiO<sub>2</sub> coatings do not provide any additional benefit.

Another trend noticed was that samples with oxidized surfaces (either the air oxidized or deposited protective oxide) with low  $\epsilon$ , tend to increase in  $\epsilon$  with initial VHT exposure. While those with initially high  $\epsilon$  ( $\approx 0.80$ ) only decrease with VHT exposure. In addition, the samples which start with a lower  $\epsilon$  and increase with VHT exposure then tend to be more durable than those with an initially high  $\epsilon$ . This trend can be observed in Figures 4 and 7.

##### Comparison of C and SiC Arc texturing VHT Durability.

The unexposed carbon arc textured surface appeared uniformly black and had a high  $\epsilon$  (ave. of 0.82). Unfortunately this sample was found to degrade rapidly with VHT exposure, as can be seen in Figure 8. The surface after VHT exposure was very light colored, and it appeared that the incorporated carbon was evaporated from the surface, resulting in the  $\epsilon$  decrease. Be-

cause of the loss of the C, SiC arc texturing was evaluated with the hope that SiC would be incorporated into the Haynes surface and a SiO<sub>2</sub> protective layer would develop with background oxygen during VHT exposure. The SiC arc textured surface was found to be more VHT durable than the C arc textured surface, but the SiC arc textured surface also degraded rapidly with VHT exposure (see Figure 8). This surface also changed from a black appearance to a light appearance with VHT exposure.

The application of CVD and PVD SiO<sub>2</sub> protective coatings onto the C arc textured surface resulted in improved VHT durability as can be seen in Figure 8. In this case, the CVD coating process was found to provide much greater protection than the PVD process. These results are consistent with anticipated results for PVD and CVD protective coatings. Even the best arc textured performer, CVD SiO<sub>2</sub> coated C arc textured, was found to drop significantly in  $\epsilon$  with VHT exposure, making arc texturing undesirable even though the initial  $\epsilon$  was very high.

**Effect of Coating Thickness (ZB-1 and AB) on VHT Durability.** The initial  $\epsilon$  values of Haynes 188 samples with ZB-1 coatings were between 0.71 and 0.75. These values were found to increase rather significantly with VHT exposure (see Figure 9). The 0.254 mm thick ZB-1 coating increased to 0.89 after 316.5 hours, and the 0.025-0.104 mm thick ZB-1 coatings increased to 0.85 after 555.5 hours of VHT exposure. These effects are attributed to stoichiometric changes which occur under VHT exposure.<sup>9</sup> These samples were found to be very durable to VHT exposure. Samples with 0.025-0.104 mm ZB-1 coatings reacted very similarly to each other with no coating thickness effect, as can be seen in Figure 9, and had an average resulting  $\epsilon$  of 0.83 after 1159.3 hours and 13 thermal cycles. This value is higher than the average initial value of 0.73. The two samples with 0.254 mm ZB-1 coatings performed even better than the thinner coatings, with a final  $\epsilon$  of 0.86 after 2024.3 hours of VHT exposure with 25 thermal cycles. There was no physical degradation of (embrittlement, coating spalling, etc.) noticed with these samples.

Samples with AB coatings, 0.025 mm and 0.051 mm thick, were found to be very VHT durable. Both of these samples started with a very high initial  $\epsilon$  of 0.86 and then further increased to 0.89 after 984.2 hours of VHT exposure (see Figure 10). Again, this is probably attributed to stoichiometric changes with VHT exposure. These samples, reacting almost identically, were then found to drop in  $\epsilon$  to only 0.85, essentially the initial  $\epsilon$ , after 2692 hours of VHT exposure with 32 thermal cycles. There was no physical degradation noticed with the AB coatings.

**Comparison of Surface Modification VHT Durabilities.** The three graphs in Figure 11 display the  $\epsilon$  VHT durability for all 35 samples tested. The requirement for the SD GTD receiver was to maintain an  $\epsilon$  of at least 0.70 for 1000 hours. The samples are graphed in the order in which they were introduced into the vacuum furnace. Lines are drawn on the graphs at 1000 hrs and  $\epsilon = 0.70$  to help visualize which samples meet the specified requirements. A total of 12 samples were found to

have maintained an  $\epsilon$  of at least 0.7 after 1000 hours of VHT exposure; 2 shown in Figure 11a (982°C/16 hrs and 982°C/16 hrs PVD SiO<sub>2</sub> coated), 4 shown in 11b (982°C/4 hrs CVD SiO<sub>2</sub> coated, 982°C/16 hrs CVD SiO<sub>2</sub> coated, 0.025 mm and 0.051 mm AB coatings), and 6 shown in 11c (ZB-1 coatings: 0.025 mm, 0.056 mm, 0.071 mm, 0.104 mm, and 2 with 0.254 mm).

Table 5 provides a summary of the optical properties and VHT exposures for the 12 samples meeting the SD GTD requirement. Averaged values are given for the following 3 groups of samples due to similar samples displaying near identical performance: AB coatings (0.025 mm & 0.051 mm), ZB-1 coatings (0.025-0.104 mm) and ZB-1 coatings (0.254 mm). The summary table therefore lists 7 surface treatments. Figure 12 compares the performance and VHT durability of the samples which received the 7 Haynes 188 surface treatments meeting the emittance durability requirement.

Samples with 0.025 mm and 0.051 mm thick AB coatings and 0.254 mm ZB-1 coatings had excellent VHT performance. Because the samples with AB coatings had higher initial  $\epsilon$ , slightly higher  $\epsilon$  after VHT, and received longer VHT exposure (which provided performance data earlier in the program), the AB coating was chosen for the  $\epsilon$  enhancement surface modification technique for the SD GTD receiver. Because both the 0.025 mm and the 0.051 mm thick AB coatings performed essentially identically, the 0.025 mm coating was chosen for thermal conductivity purposes. In addition to being chosen for the receiver canisters, because of the outstanding thermal  $\epsilon$  and VHT durability, the 0.025 mm AB coating was also chosen for emittance enhancement for the SD GTD parasitic load radiator (PLR). The PLR functions as an electrical sink for excess power from the turboalternator/compressor, and will also be located in the thermal vacuum environment.<sup>2</sup>

## CONCLUSIONS

Surface modification was found to increase the emittance of Haynes 188 from 0.11 to between 0.28 and 0.86. Four techniques were found to increase the  $\epsilon$  to the desired value of 0.80, or above. These techniques were: the application of an alumina based coating, carbon arc texturing, SiC arc texturing, and SiC grit blasting followed by air oxidation at 871°C. The resulting  $\epsilon$  values obtained by these techniques were 0.86, 0.82, 0.80 and 0.80, respectively. Comparisons of air oxidation temperature and time, mechanical texturing vs. grit blasting prior to air oxidation, AB and ZB-1 coating thicknesses, C vs. SiC arc texturing, and application of a SiO<sub>2</sub> or AlO<sub>3</sub> protective coating, were individually analyzed for effects on both as-treated optical performance and VHT durability.

Of the 35 emittance enhanced Haynes 188 samples, 12 samples corresponding to 7 surface treatments were found to meet the solar dynamic ground test demonstrator VHT durability requirement ( $\epsilon \geq 0.70$  for 1,000 hrs). None of the 12 samples tested were found to display any evidence of embrittlement or threat of spalling of the high emittance surface after VHT exposure with integral thermal cycling. Of the 7 surface treatments, 2 were found to display excellent VHT durability, 0.025 mm -



0.051 mm alumina based coatings ( $\epsilon = 0.85$  after 2695 VHT hrs with 32 thermal cycles) and 0.254 mm zirconia based coatings with composition #1 ( $\epsilon = 0.86$  after 2024.3 hrs with 25 thermal cycles). Because the alumina based coatings had higher initial  $\epsilon$ , slightly higher  $\epsilon$  after VHT, and received longer VHT exposure (which provided performance data earlier in the program), the 0.025 mm thick alumina based coating was chosen for the  $\epsilon$  enhancement surface modification technique for the SD GTD receiver.

The success of finding a very high emittance coating which is durable to VHT will help to ensure successful demonstration of solar dynamic power generation for space applications, and has potential for applications in other systems requiring high emittance surfaces. Based on these findings, the alumina based coating has already been chosen for emittance enhancement for the SD GTD parasitic load radiator in addition to the heat receiver canisters.

## ACKNOWLEDGEMENTS

The authors would like to acknowledge several people whose help greatly contributed to this research project. We would like to thank: Dr. D. A. Gulino of Ohio University for coating samples with CVD  $\text{SiO}_2$  and CVD  $\text{Al}_2\text{O}_3$ , Dr. R. A. Miller of NASA LeRC and G. W. Leissler of Sverdrup Technology for coating samples with ZB-1 and ZB-2, M. Forkapa of CSU for arc texturing samples, and C. R. Stidham for thermal analysis. Finally the authors would like to send their greatest appreciation to Dr. J. D. Whittenberger of NASA LeRC for providing the many hours of vacuum furnace exposure for our samples.

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Table 1. Summary of the Effect of Surface Modification on the Optical Properties of Haynes 188

| Legend   | Surface Treatment  | $\epsilon_{827^\circ\text{C}}$ | $\epsilon_{827^\circ\text{C}^*}$ | $\alpha_s$ |
|----------|--|--------------------------------|----------------------------------|------------|
| Pristine | Pristine   | 0.14                           | 0.08                             | 0.370      |
| AB       | Alumina based coating (0.025 mm & 0.051 mm thick), ave. of 2               | -                              | 0.86                             | 0.934      |
| C-AT     | Carbon arc textured  | 0.77                           | 0.86                             | 0.906      |
| SiC-AT   | SiC arc textured   | -                              | 0.80                             | 0.914      |
| 871C     | SiC grit blast & air oxidized (871°C: 3, 6 & 24 hrs), ave. of 3            | 0.79                           | 0.80                             | 0.905      |
| ZB-1     | Zirconia based coating, composition #1 (0.025 - 0.254 mm thick), ave. of 6 | -                              | 0.73                             | 0.858      |
| 982C     | SiC grit blast & air oxidized (982°C: 2, 4 & 16 hrs), ave. of 3            | 0.72                           | 0.72                             | 0.892      |
| Mech/Ox  | Mechanically indented & air oxidized (871°C, 24 hrs)                       | 0.68                           | 0.67                             | 0.890      |
| Mech/G   | Mechanically indented w/ graphite application                              | 0.42                           | -                                | 0.516      |
| ZB-2     | Zirconia based coating, composition #2 (0.254 mm thick), ave. of 2         | -                              | 0.40                             | 0.613      |
| Laser    | Laser Treated  | 0.28                           | -                                | 0.774      |

Table 2. Effect of Air Oxidation, With and Without Protective Coatings, on the Optical Properties of Haynes 188

| Surface Treatment  | $\epsilon_{827^\circ\text{C}}$ | $\epsilon_{827^\circ\text{C}^*}$ | $\alpha_s$ |
|--|--------------------------------|----------------------------------|------------|
| SiC grit blast (GB) & air oxidized (871°C, 3 hrs)                              | 0.80                           | 0.80                             | 0.898      |
| SiC GB, air oxidized (871°C/6 hrs)   | 0.79                           | 0.79                             | 0.904      |
| SiC GB, air oxidized (871°C/24 hrs)  | 0.77                           | -                                | 0.912      |
| Mech. indented, air oxidized (871°C/24 hrs)                                    | 0.68                           | 0.67                             | 0.890      |
| SiC GB, air oxidized (982°C/2 hrs)   | 0.72                           | 0.74                             | 0.889      |
| SiC GB, air oxidized (982°C/4 hrs)   | 0.72                           | 0.70                             | 0.893      |
| SiC GB, air oxidized (982°C/16 hrs)  | 0.71                           | -                                | 0.894      |
| SiC GB, air oxidized (871°C/3 hrs), CVD SiO <sub>2</sub>                       | -                              | 0.77                             | 0.934      |
| SiC GB, air oxidized (871°C/6 hrs), CVD SiO <sub>2</sub>                       | -                              | 0.75                             | 0.939      |
| Mech. indent, air ox. (871°C/6 hrs), CVD SiO <sub>2</sub>                      | -                              | 0.55                             | 0.918      |
| SiC GB, air oxidized (871°C/24 hrs), PVD SiO <sub>2</sub>                      | 0.80                           | -                                | 0.946      |
| SiC GB, air ox. (871°C/24 hrs), CVD SiO <sub>2</sub> , ave. of 2               | -                              | 0.79                             | 0.942      |
| SiC GB, air ox. (871°C/24 hrs), CVD Al <sub>2</sub> O <sub>3</sub> , ave. of 2 | -                              | 0.77                             | 0.936      |
| SiC GB, air oxidized (982°C/2 hrs), CVD SiO <sub>2</sub>                       | -                              | 0.57                             | 0.921      |
| SiC GB, air oxidized (982°C/4 hrs), CVD SiO <sub>2</sub>                       | -                              | 0.54                             | 0.913      |
| SiC GB, air oxidized (982°C/16 hrs), PVD SiO <sub>2</sub>                      | 0.73                           | -                                | 0.919      |
| SiC GB, air oxidized (982°C/16 hrs), CVD SiO <sub>2</sub>                      | -                              | 0.58                             | 0.921      |

Table 3. Effect of AB or ZB-1 Coating Thickness on the Optical Properties of Haynes 188

| Surface Treatment                                     | $\epsilon_{827^\circ\text{C}}$ | $\alpha_s$ |
|---|--------------------------------|------------|
| Alumina based coating (AB), 0.025 mm                  | 0.86                           | 0.935      |
| Alumina based coating (AB), 0.051 mm                  | 0.86                           | 0.932      |
| Zirconia based coating #1 (ZB-1), 0.025 mm            | 0.75                           | 0.879      |
| Zirconia based coating #1 (ZB-1), 0.056 mm            | 0.73                           | 0.859      |
| Zirconia based coating #1 (ZB-1), 0.071 mm            | 0.72                           | 0.855      |
| Zirconia based coating #1 (ZB-1), 0.104 mm            | 0.72                           | 0.851      |
| Zirconia based coating #1 (ZB-1), 0.254 mm, ave. of 2 | 0.72                           | 0.852      |

Table 4. Effect of Arc Texturing, With and Without Protective Coatings, on the Optical Properties of Haynes 188

| Surface Treatment                                | $\epsilon_{827^\circ\text{C}}$ | $\epsilon_{827^\circ\text{C}}$ | $\alpha_s$ |
|--|--------------------------------|--------------------------------|------------|
| Carbon arc textured                              | 0.77                           | 0.86                           | 0.906      |
| SiC arc textured                                 | -                              | 0.80                           | 0.914      |
| Mechanically indented w/ graphite application    | 0.42                           | -                              | 0.516      |
| Carbon arc textured, PVD SiO <sub>2</sub> coated | 0.80                           | -                              | 0.947      |
| Carbon arc textured, CVD SiO <sub>2</sub> coated | -                              | 0.98                           | 0.969      |

Table 5. Vacuum Heat Treatment Durability Performance of Surface Modified Haynes 188

| Legend                         | Surface Treatment   | VHT Duration & Corresponding Emittance/Absorptance |  |   |   |   |
|--------------------------------|---|--|--|---|---|---|
|                                |   | 0 hrs  | 984.2 hrs  | 1532.7 hrs  | 2088.2 hrs  | 2692 hrs  |
| AB                             | Alumina based coating<br>0.025-0.051 mm thick<br>ave of 2                       | $\epsilon$ : 0.86<br>$\alpha_s$ : 0.933            | $\epsilon$ : 0.89<br>$\alpha_s$ : 0.921              | $\epsilon$ : 0.89<br>$\alpha_s$ : 0.917               | $\epsilon$ : 0.87<br>$\alpha_s$ : 0.916               | $\epsilon$ : 0.85<br>$\alpha_s$ : 0.915               |
| ZB-1<br>.025-.104 mm           | Zirconia based coating composition #1<br>0.025-0.104 mm thick<br>ave of 4       | 0 hrs<br>$\epsilon$ : 0.73<br>$\alpha_s$ : 0.861   | 555.5 hrs<br>$\epsilon$ : 0.85<br>$\alpha_s$ : 0.923 | 1159.3 hrs<br>$\epsilon$ : 0.83<br>$\alpha_s$ : 0.922 | -   | -   |
| ZB-1<br>.254 mm                | Zirconia based coating composition #1<br>0.254 mm thick<br>ave of 2             | 0 hrs<br>$\epsilon$ : 0.72<br>$\alpha_s$ : 0.852   | 316.5 hrs<br>$\epsilon$ : 0.89<br>$\alpha_s$ : 0.924 | 865 hrs<br>$\epsilon$ : 0.89<br>$\alpha_s$ : 0.926    | 1420.5 hrs<br>$\epsilon$ : 0.88<br>$\alpha_s$ : 0.936 | 2024.3 hrs<br>$\epsilon$ : 0.86<br>$\alpha_s$ : 0.938 |
| 982/16                         | SiC grit blast & air oxidized<br>(982°C, 16 hrs)                                | 0 hrs<br>$\epsilon$ : 0.71<br>$\alpha_s$ : 0.894   | 272.5 hrs<br>$\epsilon$ : 0.75<br>$\alpha_s$ : 0.900 | 940.2 hrs<br>$\epsilon$ : 0.75<br>$\alpha_s$ : 0.900  | 2044.4 hrs<br>$\epsilon$ : 0.72<br>$\alpha_s$ : 0.897 | -   |
| 982/16<br>PVD SiO <sub>2</sub> | SiC grit blast & air oxidized<br>(982°C, 16 hrs)<br>PVD SiO <sub>2</sub> coated | 0 hrs<br>$\epsilon$ : 0.73<br>$\alpha_s$ : 0.921   | 272.5 hrs<br>$\epsilon$ : 0.78<br>$\alpha_s$ : 0.931 | 889 hrs<br>$\epsilon$ : 0.77<br>$\alpha_s$ : 0.920    | 1993 hrs<br>$\epsilon$ : 0.69<br>$\alpha_s$ : 0.874   | -   |
| 982/16<br>CVD SiO <sub>2</sub> | SiC grit blast & air oxidized<br>(982°C, 16 hrs)<br>CVD SiO <sub>2</sub> coated | 0 hrs<br>$\epsilon$ : 0.58<br>$\alpha_s$ : 0.921   | 616.5 hrs<br>$\epsilon$ : 0.78<br>$\alpha_s$ : 0.938 | 1165 hrs<br>$\epsilon$ : 0.79<br>$\alpha_s$ : 0.927   | 1720.5 hrs<br>$\epsilon$ : 0.74<br>$\alpha_s$ : 0.906 | 2324.3 hrs<br>$\epsilon$ : 0.69<br>$\alpha_s$ : 0.885 |
| 982/4<br>CVD SiO <sub>2</sub>  | SiC grit blast & air oxidized<br>(982°C, 4 hrs)<br>CVD SiO <sub>2</sub> coated  | 0 hrs<br>$\epsilon$ : 0.54<br>$\alpha_s$ : 0.913   | 616.5 hrs<br>$\epsilon$ : 0.76<br>$\alpha_s$ : 0.916 | 1165 hrs<br>$\epsilon$ : 0.69<br>$\alpha_s$ : 0.882   | 1720.5 hrs<br>$\epsilon$ : 0.56<br>$\alpha_s$ : 0.819 | 2324.3 hrs<br>$\epsilon$ : 0.43<br>$\alpha_s$ : 0.741 |

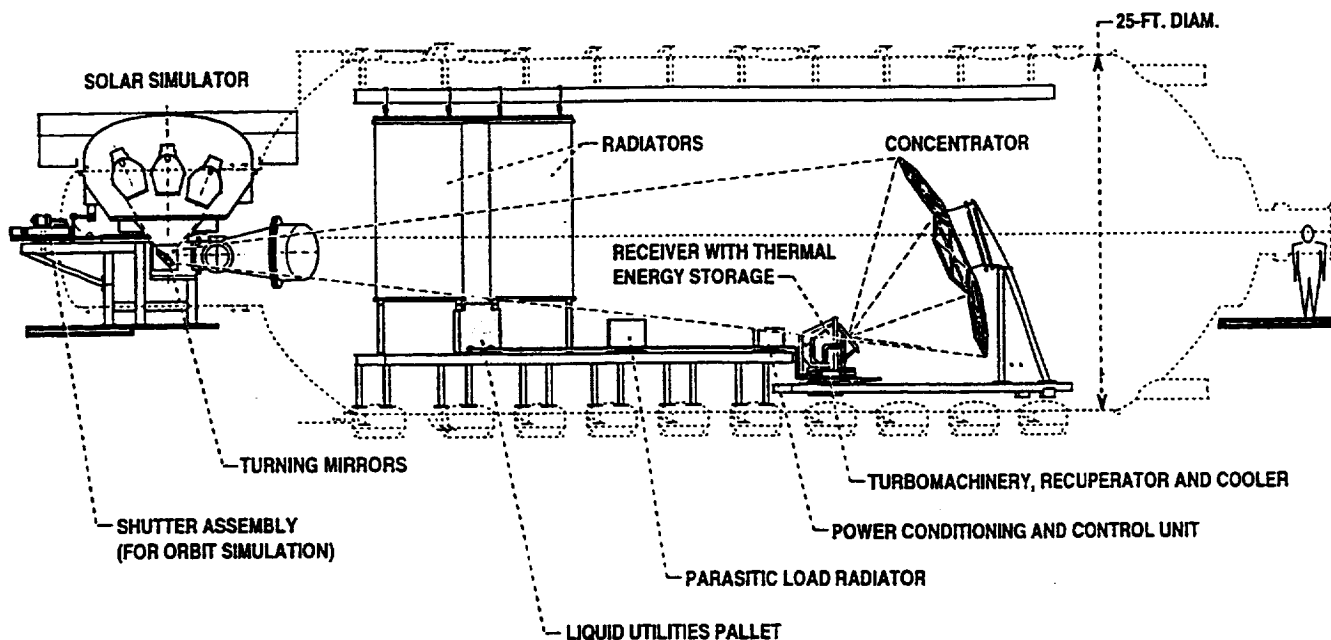


FIGURE 1. SOLAR DYNAMIC GROUND TEST DEMONSTRATOR SYSTEM IN TANK 6 AT NASA LEWIS RESEARCH CENTER.

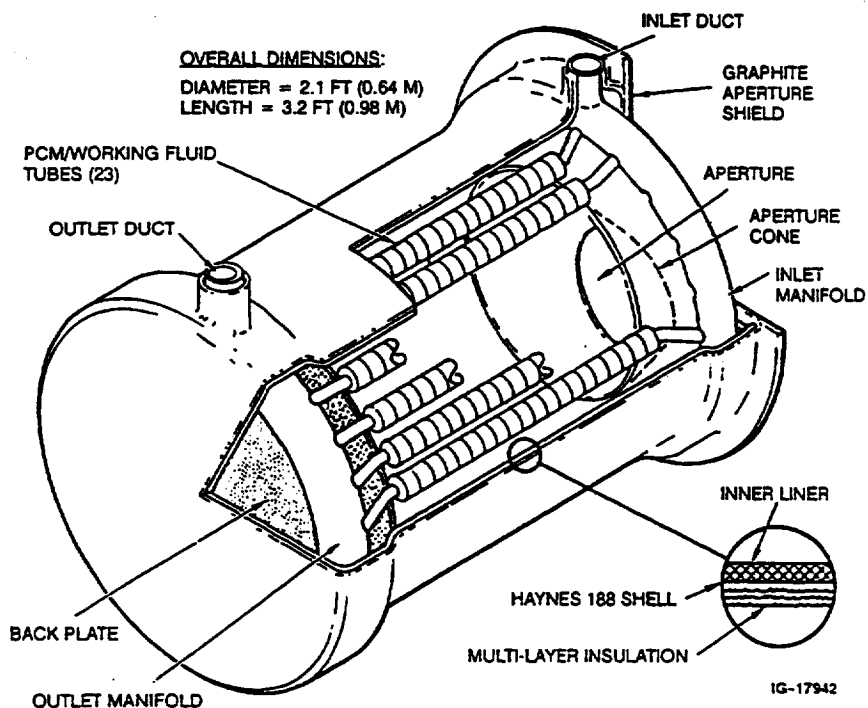


FIGURE 2. HEAT RECEIVER FOR THE 2 kW SOLAR DYNAMIC GROUND TEST DEMONSTRATOR SYSTEM.

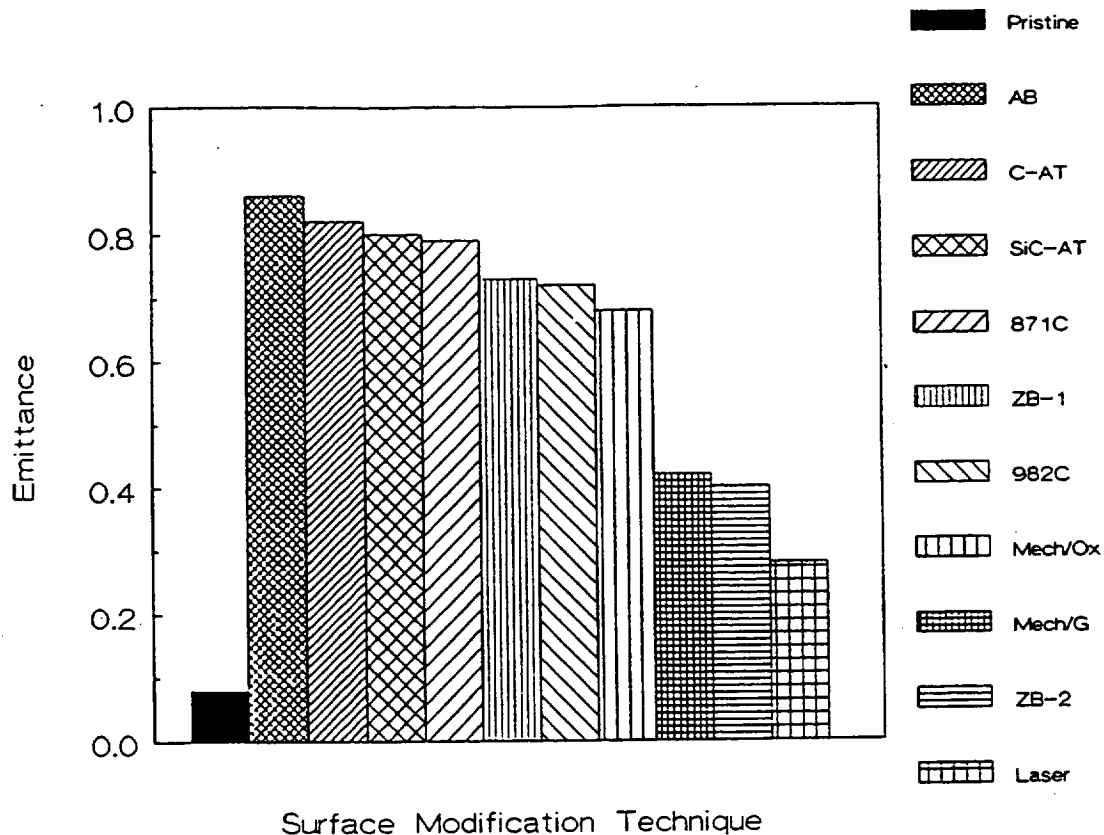


FIGURE 3. EFFECT OF SURFACE MODIFICATION ON THE EMITTANCE OF HAYNES 188.

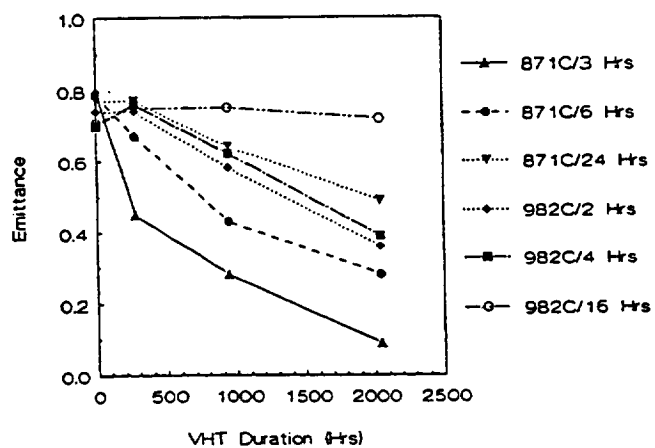


FIGURE 4. EFFECT OF AIR OXIDATION TEMPERATURE AND TIME ON THE VHT DURABILITY OF HAYNES 188.

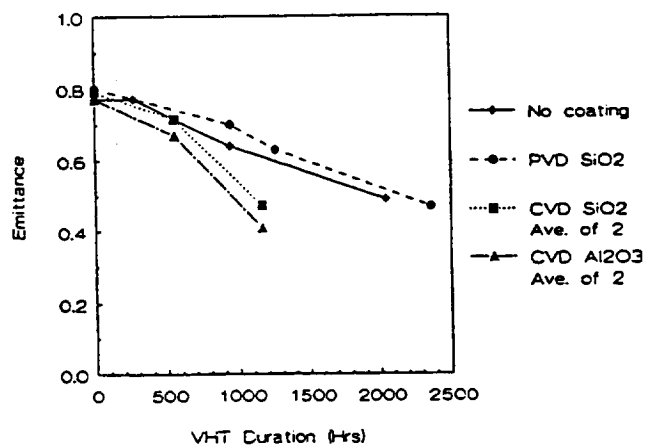


FIGURE 5. HAYNES 188 GRIT BLASTED AND AIR OXIDIZED AT 871°C FOR 24 HOURS: COMPARISON OF THE VHT DURABILITY WITH AND WITHOUT PROTECTIVE COATINGS.

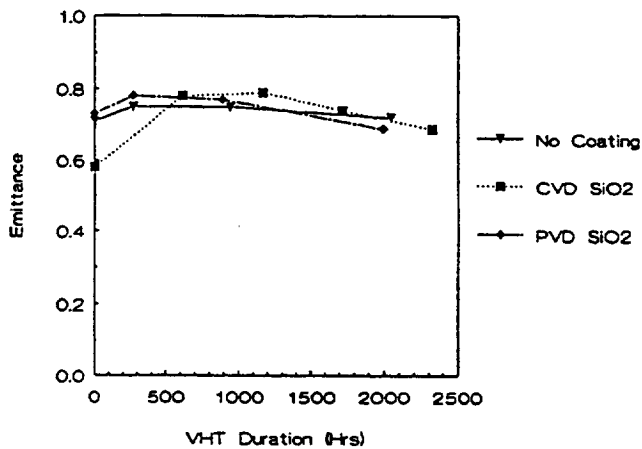


FIGURE 6. HAYNES 188 GRIT BLASTED AND AIR OXIDIZED AT 982°C FOR 16 HOURS: COMPARISON OF THE VHT DURABILITY WITH AND WITHOUT PROTECTIVE COATINGS.

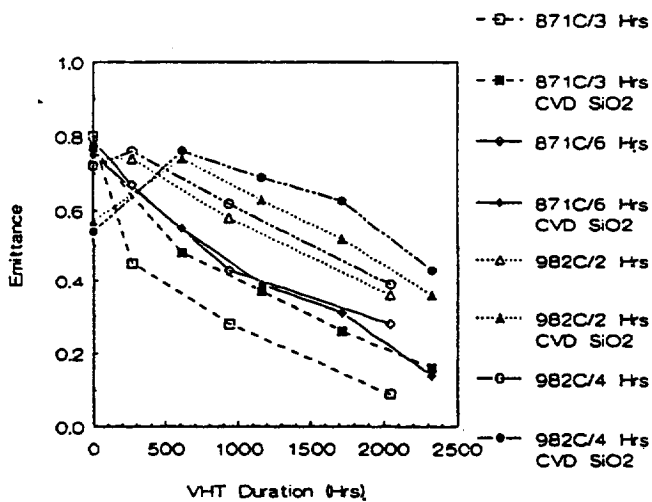


FIGURE 7. HAYNES 188 GRIT BLASTED AND AIR OXIDIZED FOR SHORT DURATIONS: COMPARISON OF THE VHT DURABILITY WITH AND WITHOUT PROTECTIVE COATINGS.

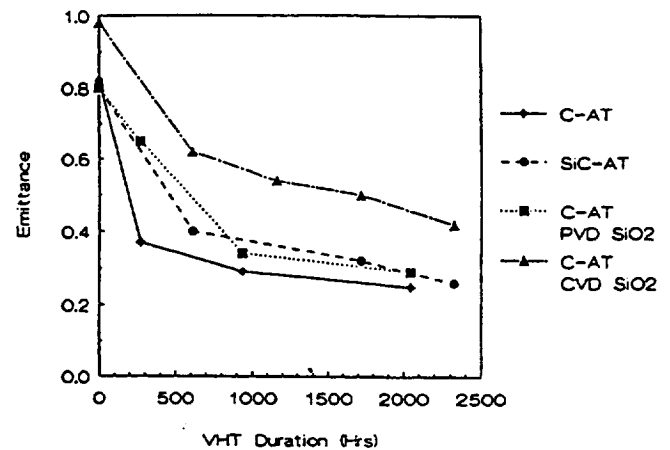


FIGURE 8. COMPARISON OF C AND SiC ARC TEXTURING, AND THE EFFECTIVENESS OF PROTECTIVE COATINGS ON C ARC TEXTURED HAYNES 188.

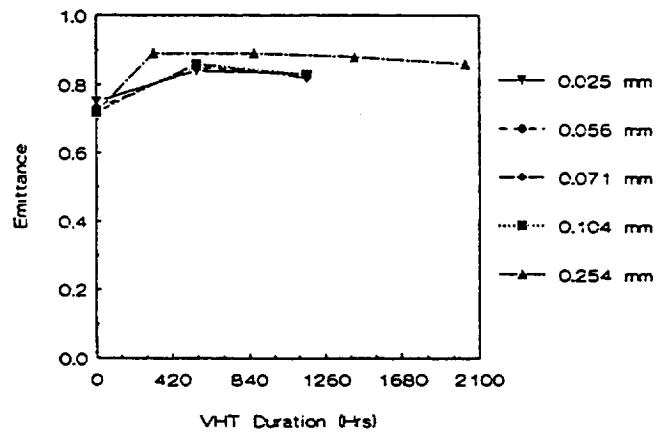


FIGURE 9. EFFECT OF COATING THICKNESS ON THE VHT DURABILITY OF ZB-1 COATED HAYNES 188.

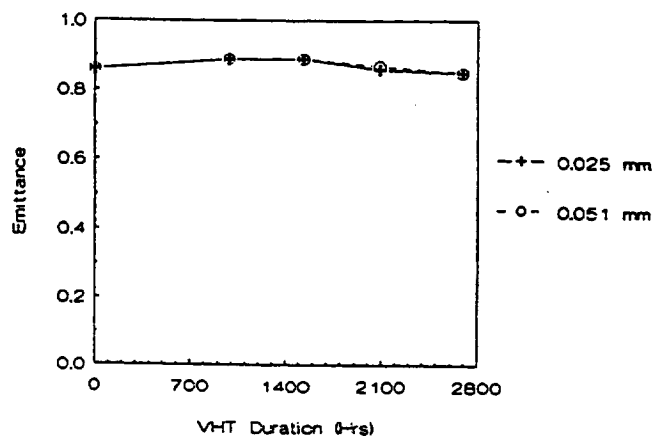
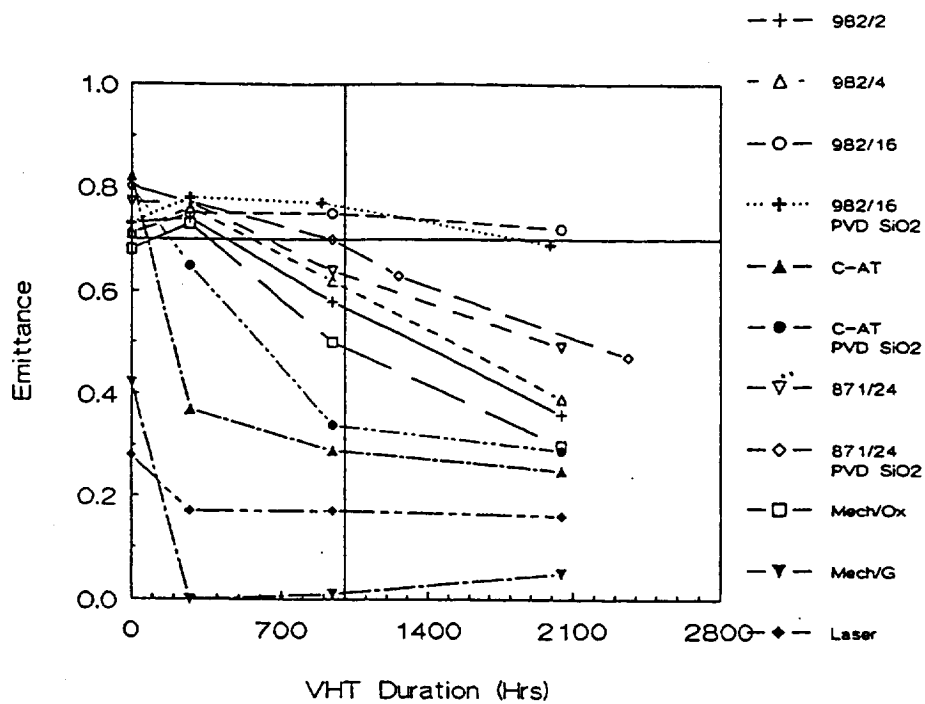
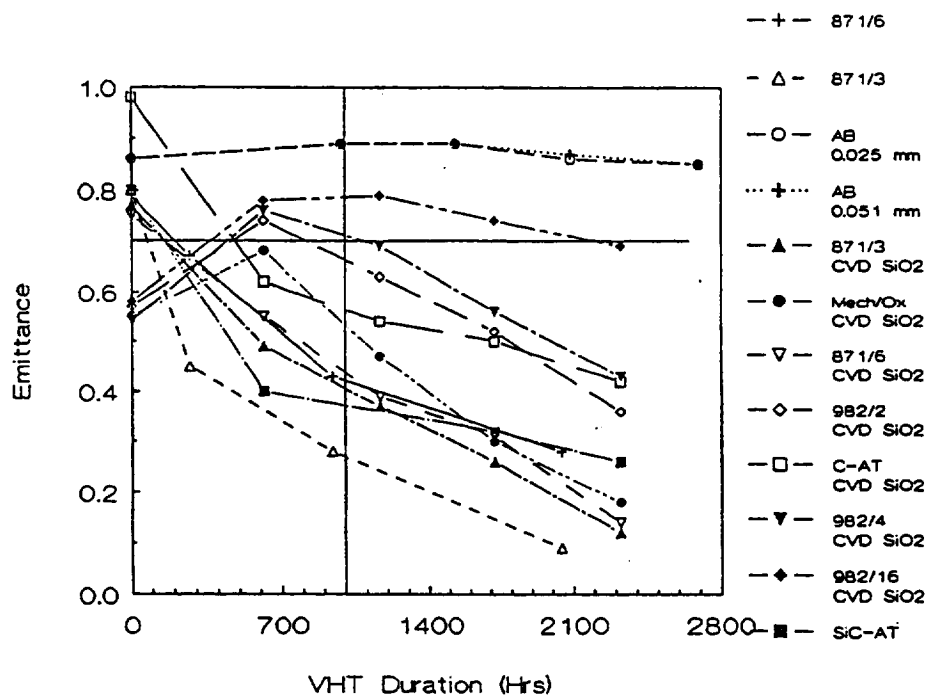


FIGURE 10. EFFECT OF COATING THICKNESS ON THE VHT DURABILITY OF AB COATED HAYNES 188.



11A.



11B.

FIGURE 11. PERFORMANCE COMPARISON OF THE VHT DURABILITY OF VARIOUS SURFACE TREATED HAYNES 188 SAMPLES. SD GTD REQUIRES AN EMITTANCE OF AT LEAST 0.7 AFTER 1000 HOURS VHT EXPOSURE.

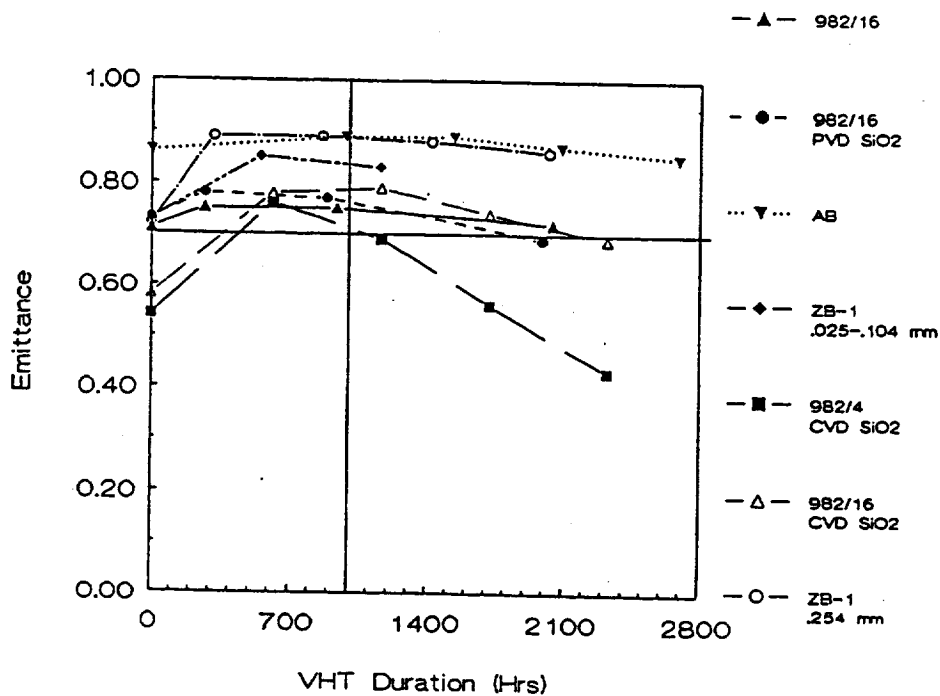
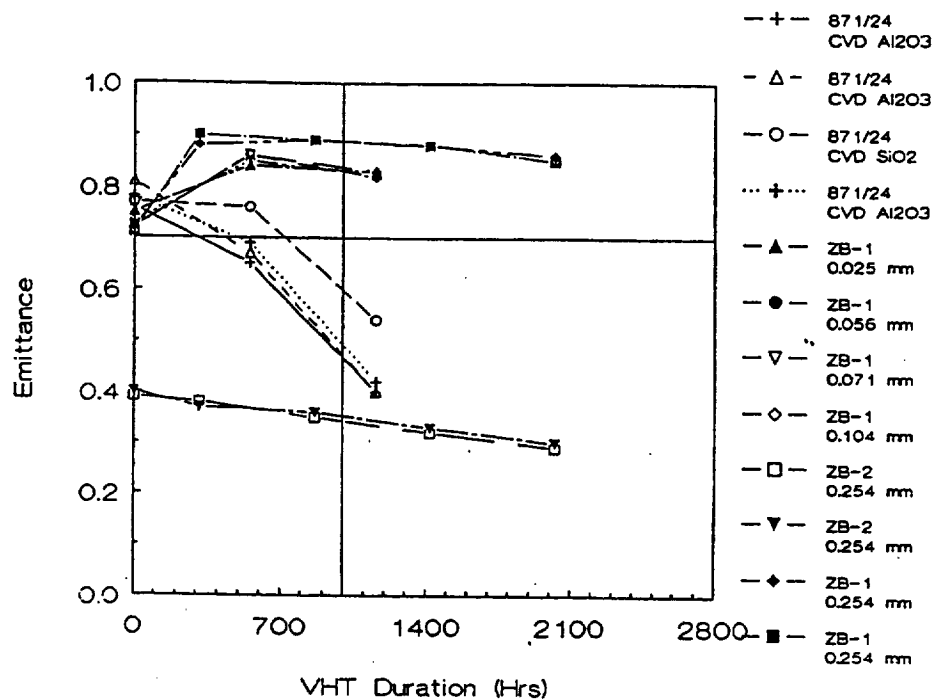


FIGURE 12. PERFORMANCE COMPARISON OF THE 7 SURFACE TREATMENTS WHICH MET THE SD GTD EMITTANCE PERFORMANCE REQUIREMENT AFTER 1000 HOURS OF VHT EXPOSURE.





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| 1. AGENCY USE ONLY (Leave blank)  |   | 2. REPORT DATE<br>March 1994                               |   | 3. REPORT TYPE AND DATES COVERED<br>Technical Memorandum |
| 4. TITLE AND SUBTITLE<br><br>Performance and Durability of High Emittance Heat Receiver Surfaces for Solar Dynamic Power Systems  |   |  | 5. FUNDING NUMBERS<br><br>WU-585-03-21                                  |  |
| 6. AUTHOR(S)<br><br>Kim K. de Groh, David M. Roig, Christopher A. Burke, and Dilipkumar R. Shah   |   |  |   |  |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br><br>National Aeronautics and Space Administration<br>Lewis Research Center<br>Cleveland, Ohio 44135-3191  |   |  | 8. PERFORMING ORGANIZATION<br>REPORT NUMBER<br><br>E-8700               |  |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)<br><br>National Aeronautics and Space Administration<br>Washington, D.C. 20546-0001   |   |  | 10. SPONSORING/MONITORING<br>AGENCY REPORT NUMBER<br><br>NASA TM-106549 |  |
| 11. SUPPLEMENTARY NOTES<br>Prepared for the 1994 ASME International Solar Energy Conference sponsored by the American Society of Mechanical Engineers, San Francisco, California, March 27-30, 1994. Kim K. de Groh, NASA Lewis Research Center; David M. Roig and Christopher A. Burke, Cleveland State University, Cleveland, Ohio 44115; and Dilipkumar R. Shah, AlliedSignal Aerospace Company, Torrance, California 90509. Responsible person, Kim K. de Groh, organization code 5480, (216) 433-2297.   |   |  |   |  |
| 12a. DISTRIBUTION/AVAILABILITY STATEMENT<br><br>Unclassified - Unlimited<br>Subject Category 20   |   |  | 12b. DISTRIBUTION CODE  |  |
| 13. ABSTRACT (Maximum 200 words)<br><br>Haynes 188, a cobalt-based superalloy, will be used to make thermal energy storage (TES) containment canisters for a 2 kW solar dynamic ground test demonstrator (SD GTD). Haynes 188 containment canisters with a high thermal emittance ( $\epsilon$ ) are desired for radiating heat away from local hot spots, improving the heating distribution, which will in turn improve canister service life. In addition to needing a high emittance, the surface needs to be durable in an elevated temperature, high vacuum ( $\approx 830^\circ\text{C}$ , $<10^{-7}$ torr) environment for an extended time period. Thirty-five Haynes 188 samples were exposed to 14 different types of surface modification techniques for emittance and vacuum heat treatment (VHT) durability enhancement evaluation. Optical properties were obtained for the modified surfaces. Emittance enhanced samples were exposed to VHT for up to 2692 hours at $827^\circ\text{C}$ and $\leq 10^{-6}$ torr with integral thermal cycling. Optical properties were taken intermittently during exposure, and after final VHT exposure. The various surface modification treatments increased the emittance of pristine Haynes 188 from 0.11 up to 0.86. Seven different surface modification techniques were found to provide surfaces which met the SD GTD receiver VHT durability requirement ( $\epsilon \geq 0.70$ after 1000 hrs). Of the 7 surface treatments, 2 were found to display excellent VHT durability: an alumina based (AB) coating ( $\epsilon = 0.85$ after 2695 VHT hrs) and a zirconia based coating ( $\epsilon = 0.86$ after 2024.3 VHT hrs). The alumina based coating was chosen for the $\epsilon$ enhancement surface modification technique for the SD GTD receiver. Details of the performance and vacuum heat treatment durability of this coating and other Haynes 188 emittance surface modification techniques are discussed. Technology from this program will lead to successful demonstration of solar dynamic power for space applications, and has potential for application in other systems requiring high emittance surfaces. |   |  |   |  |
| 14. SUBJECT TERMS<br><br>Thermal emittance; Solar absorptance; Vacuum heat treatment; Haynes 188;<br>Solar dynamic ground test demonstrator; Surface modification   |   |  | 15. NUMBER OF PAGES<br>16   |  |
|   |   |  | 16. PRICE CODE<br>A03   |  |
| 17. SECURITY CLASSIFICATION<br>OF REPORT<br>Unclassified  | 18. SECURITY CLASSIFICATION<br>OF THIS PAGE<br>Unclassified | 19. SECURITY CLASSIFICATION<br>OF ABSTRACT<br>Unclassified | 20. LIMITATION OF ABSTRACT  |  |